

Title of the Grant: Ultrasonic Nondestructive Characterization Of Adhesive Bonds

Type of Report: Annual Performance Report

Name of Principle Investigator: Jianmin Qu

Period Covered: 12/23/96 – 12/22/97

Grantee's Institution: Georgia Institute of Technology, Atlanta, GA 30332

Grant Number: NAG-1-1810

IN 38-CR
OSIT
125748

Introduction

Qualitative measurements of adhesion or binding forces can be accomplished, for example, by using the reflection coefficient of an ultrasound or by using thermal waves (Light and Kwun, 1989, Achenbach and Parikh, 1991, and Bostrom and wickham, 1991). However, a quantitative determination of binding forces is rather difficult. It has been observed that higher harmonics of the fundamental frequency are generated when an ultrasound passes through a nonlinear material. It seems that such non-linearity can be effectively used to characterize the bond strength. Several theories have been developed to model this nonlinear effect (Adler and Nagy, 1991; Achenbach and Parikh, 1991; Parikh and Achenbach, 1992; and Hirose and Kitahara, 1992; Anastasi and Roberts, 1992). Based on a microscopic description of the nonlinear interface binding force, a quantitative method was presented by Pangraz and Arnold (1994). Recently, Tang, Cheng and Achenbach (1997) made a comparison between the experimental and simulated results based on this theoretical model. A water immersion mode-converted shear wave through-transmission setup was used by Berndt and Green (1997) to analyze the nonlinear acoustic behavior of the adhesive bond.

In this project, the nonlinear responses of an adhesive joint was investigated through transmission tests of ultrasonic wave and analyzed by the finite element simulations. The higher order harmonics were obtained in the tests. It is found that the amplitude of higher harmonics increases as the aging increases, especially the 3rd order harmonics. Results from the numerical simulation show that the material nonlinearity does indeed generate higher order harmonics. In particular, the elastic-perfect plastic behavior generates significant 3rd and 5th order harmonics.

Through Transmission Test

Through transmission tests were conducted on the bond samples provided by NASA. The objective is to correlate the aging time of the bond joint with the generation of higher harmonics in the through transmission tests. Details of the test and some major results are described below.

Experimental Setup

A block diagram of the experimental set up is shown in Fig 1. A 40 cycle time-harmonic signal of 2MHz was generated by a Wavetek function generator (the limit frequency is 50MHz). The signal was amplified by a high voltage amplifier (ENT, DC ~

10MHz, 50dB) to obtain a high amplitude driving voltage of the generating transducer. Typical output signals of the function generator and the amplifier are shown in Fig.2. The highest output voltage of the amplifier used in the experiments was 350 volts. A narrow-band contact PZT transducer was used as the generating transducer. Its center frequency is 2MHz. The incident ultrasonic wave from the generating transducer was transmitted perpendicularly through the adhesive layer. The receiver is a broad-band contact PZT transducer with 2MHz center frequency. The output signal $f(t)$ of the receiver was recorded by an oscilloscope (Techtronix, 150MHz) and analyzed on a personal computer.

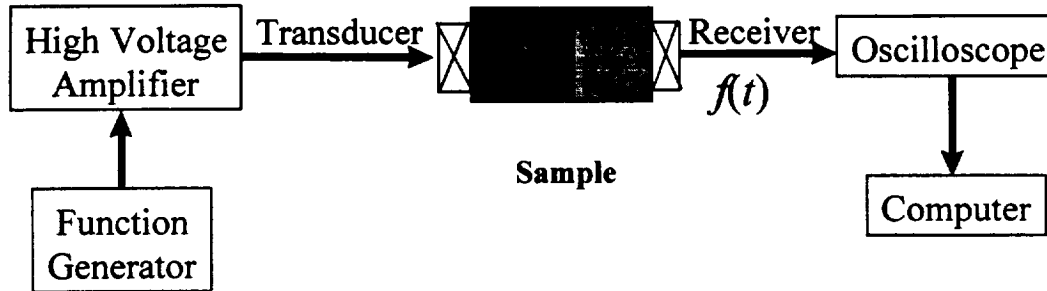


Fig.1 Experimental setup.

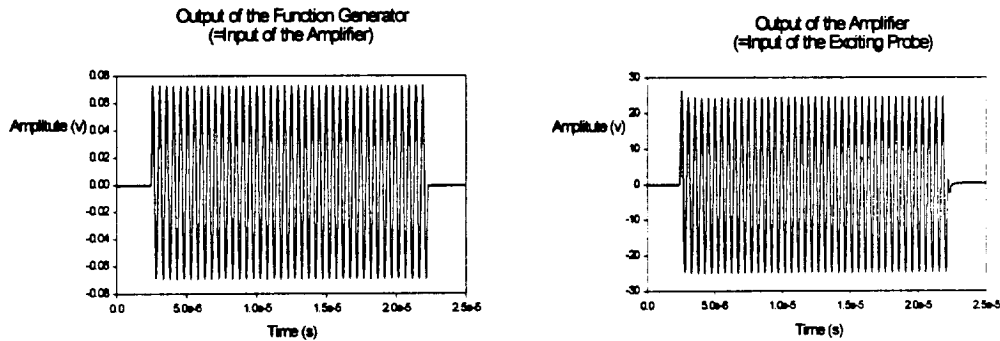


Fig.2 Typical output signals of the function generator and the amplifier.

The sample and the two contact PZT transducers were fixed by two aluminum plates with a cavity on each side, respectively, to hold the transducers at the same position (see Fig. 3). For efficient signal generation, the two transducers can be held tightly by adjusting the four bolts.

Another setup (Fig.4) was tried with a single crystal quartz transducer as the sending probe. A laser interferometer was used as the receiver. It is a broad-band green laser system and the frequency response is from 0 to 10MHz. Due to the inefficiency of the single crystal quartz transducer, we did not obtain high enough ultrasound signal to drive the interface into the nonlinear range. More work is need on this technique for year 3.

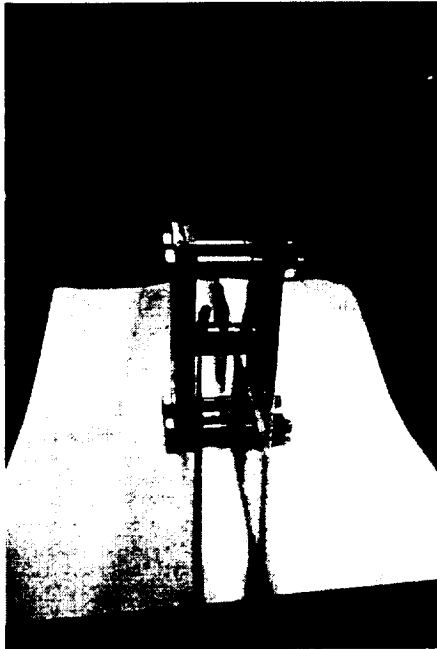


Fig. 3 Adhesive bond sample and the holding of the transducers.

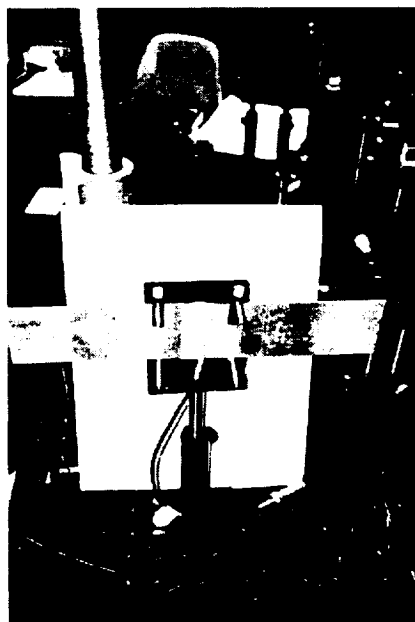


Fig.4 Single crystal quartz transducer.

Experimental Results

A typical sample received from NASA is shown in Fig. 5. Two aluminum plates were bonded together by an adhesive layer. The materials are given below:

Adherend Material: AL2024

Adhesive: FM-300 Sheet Form (carrier – nylon material)

Bonded Area: 2.0" x 1.0" in overlap, 0.003" in thickness.

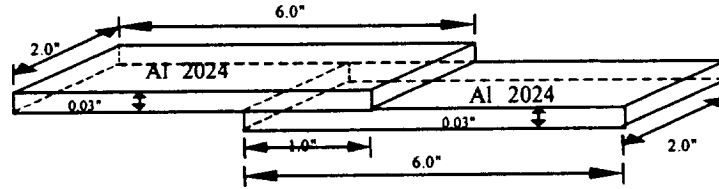


Fig.5 Adhesive bond sample geometry

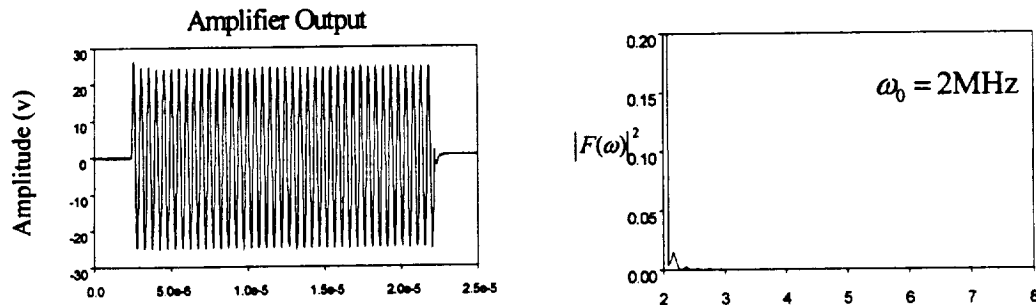
The ultrasound signal $f(t)$ received by the receiver were recorded along with the increasing driving voltages of the sending transducer. Then, the data were analyzed by the Fast Fourier Transform to obtain the frequency spectra,

$$F(\omega) = \int_0^{\infty} f(t) \exp(i\omega t) dt. \quad (1)$$

The amplitude of the fundamental frequency and the higher harmonic components are defined as

$$A_n = |F(n\omega_0)|, \quad n = 1, 2, 3 \dots \quad (2)$$

where $\omega_0 = 2\text{MHz}$.



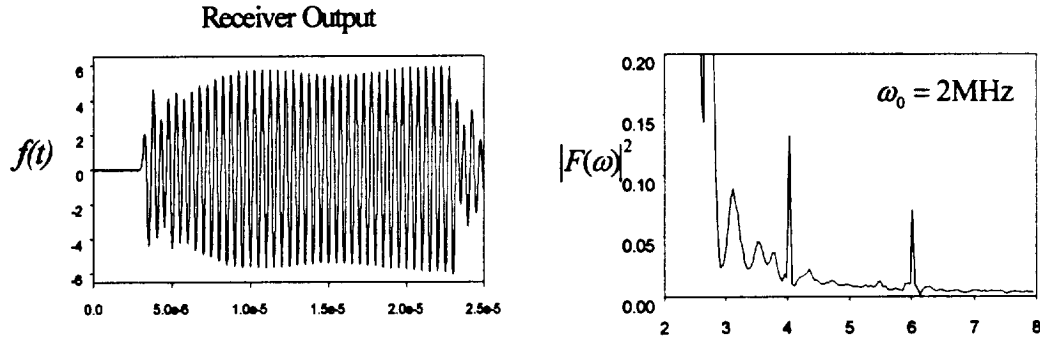


Fig. 6 Input and received signals and their frequency spectra

Examples of the output signals from the amplifier and the receiver are given in Fig. 6. Their frequency spectra are given in the same figure. It is seen that higher harmonic components were indeed generated by the nonlinear responses of the adhesive bond sample.

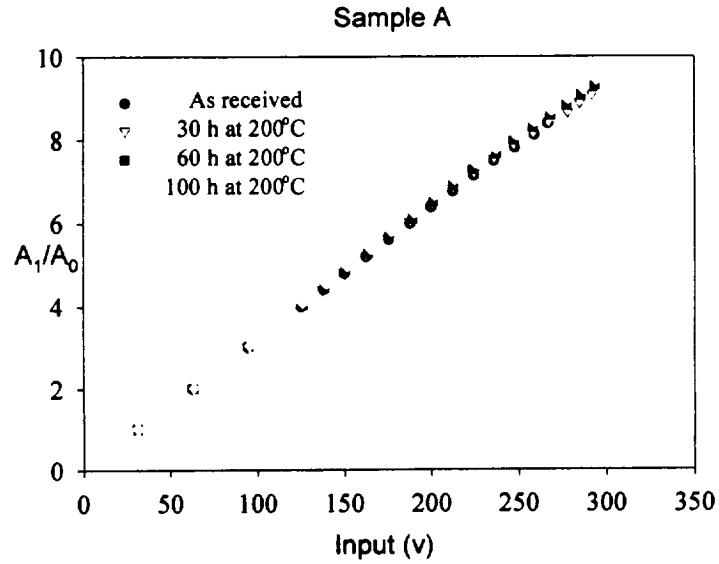


Fig. 7a Amplitude A_1 for sample A

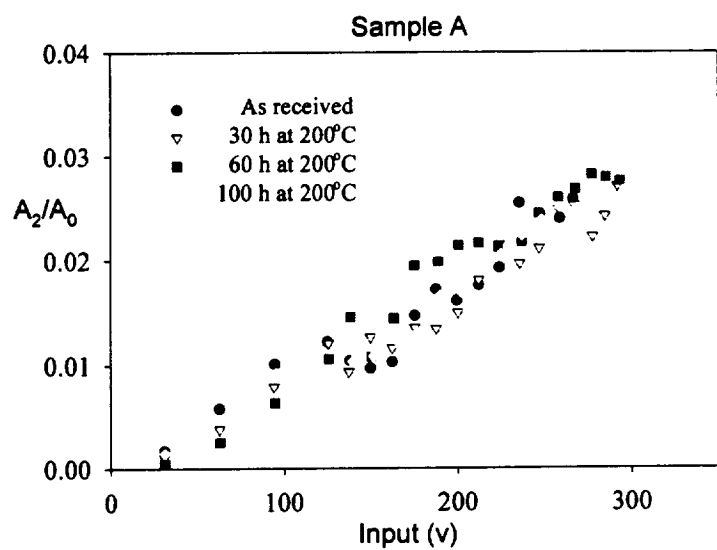


Fig. 7b Amplitude A_2 for sample A

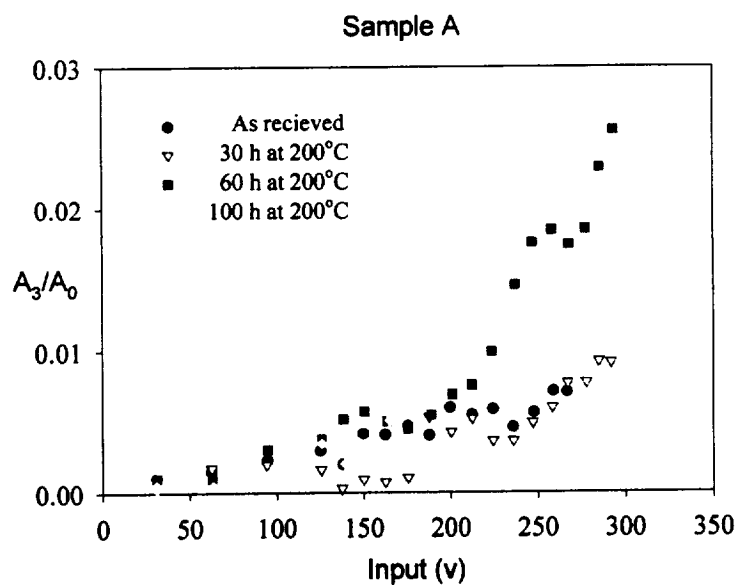


Fig. 7c Amplitude A_3 for sample A

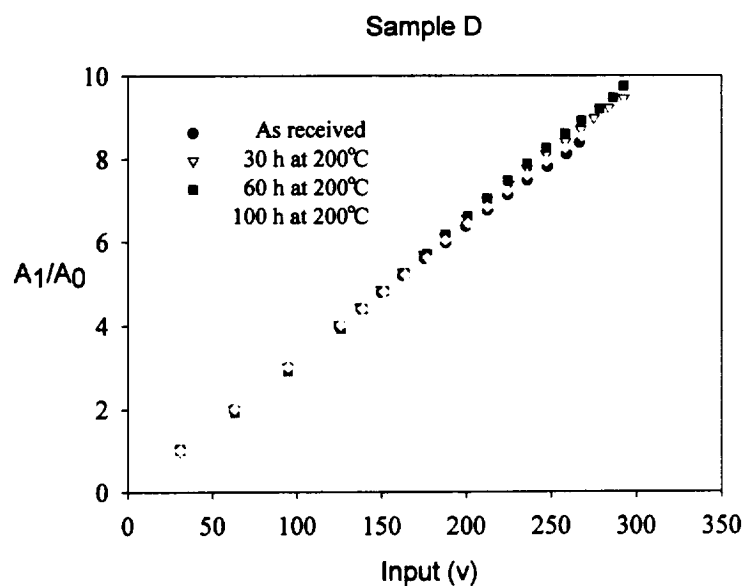


Fig. 8a Amplitude A_1 for sample D

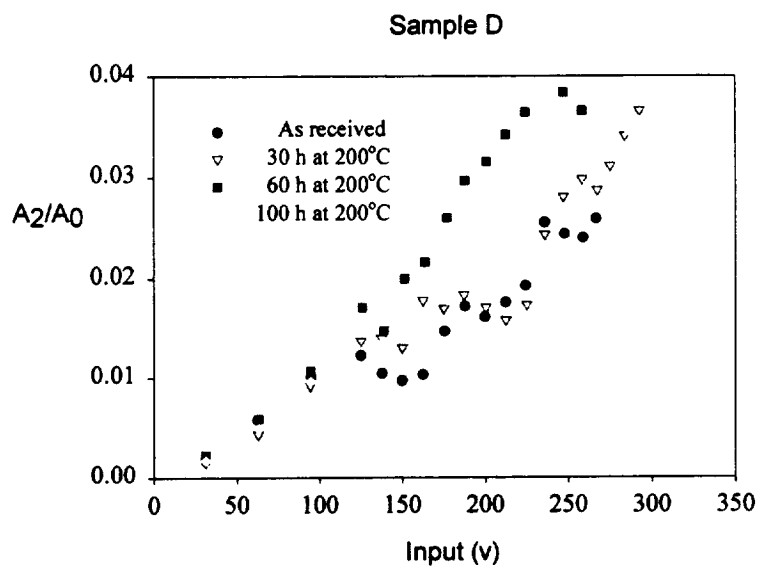


Fig. 8b Amplitude A_2 for sample D

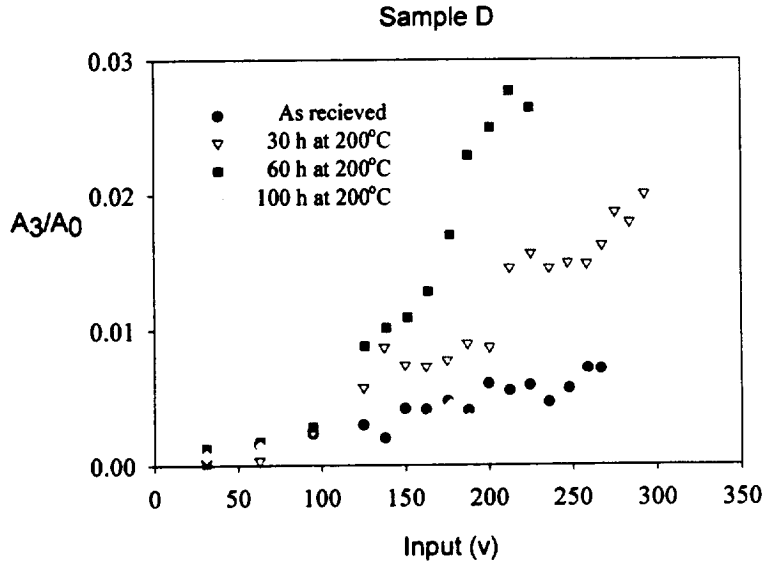


Fig. 8c Amplitude A_3 for sample D

Two samples were tested in the condition as received. Then they were placed in a oven for dry aging at 400°F for 30 hours, 60 hours, and 100 hours, respectively. At each aging increment, the samples were taken out of the oven and ultrasonic through transmission tests were performed. The resulted A_i as functions of the driving voltage of the sending probe for the two samples A and D are shown in Fig. 7 and Fig. 8, respectively. All results have been normalized by the amplitude of the fundamental component at the lowest driving voltage.

From Figs. 7 - 8, it is observed that (1) the fundamental component is the dominant one. Its amplitude is much higher than other components, (2) aging increases the magnitude of higher order harmonics of the fundamental frequency, and (3) The magnitude of the 3rd harmonics seems to correlate with aging time fairly well.

Finite Element Analysis

To understand the nonlinear effects of the adhesive layer, transmission through an adhesive layer was analyzed by the finite element method. Elastic-perfect plastic constitutive law was used for the adhesive. The input signals of 0.5MHz and 2MHz are considered.

The 1-D numerical model is shown in Fig. 9. A 5 cycle harmonic load of 0.5MHz or 2MHz was applied, respectively, as the input. The thickness of the adhesive layer is 0.003in, which is expressed as $k\lambda$ Fig. 9, where λ is the wavelength of the input signal and k is the ratio of the adhesive thickness and the wavelength. Here $\lambda = 13.036\text{mm}$ for 0.5MHz and $\lambda = 3.259\text{mm}$ for 2MHz. The corresponding k is 0.0006 and 0.0234. The adhesive layer is much thinner than the aluminum plate. So, the thickness of aluminum

parts can be assumed as infinite in the finite element analysis. The stress-strain relations are shown in Fig.10 for the aluminum and the adhesive, respectively.

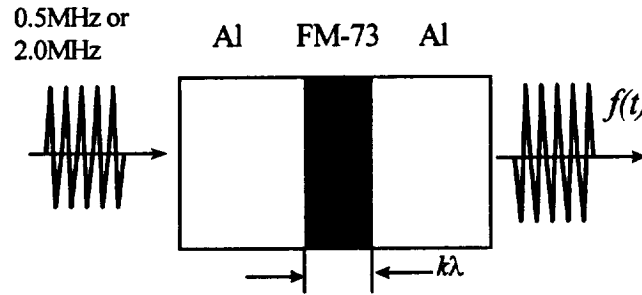


Fig. 9 Finite Element Model

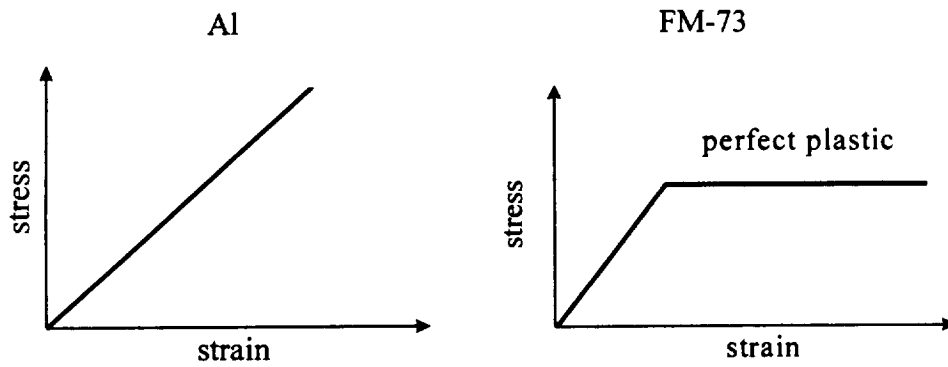


Fig.10 Stress-strain relations of Al and FM-73

Numerical results for the ultrasonic signals at three different points in the aluminum and the adhesive layer for the two loading cases are given in Fig. 11 and Fig. 12, respectively.

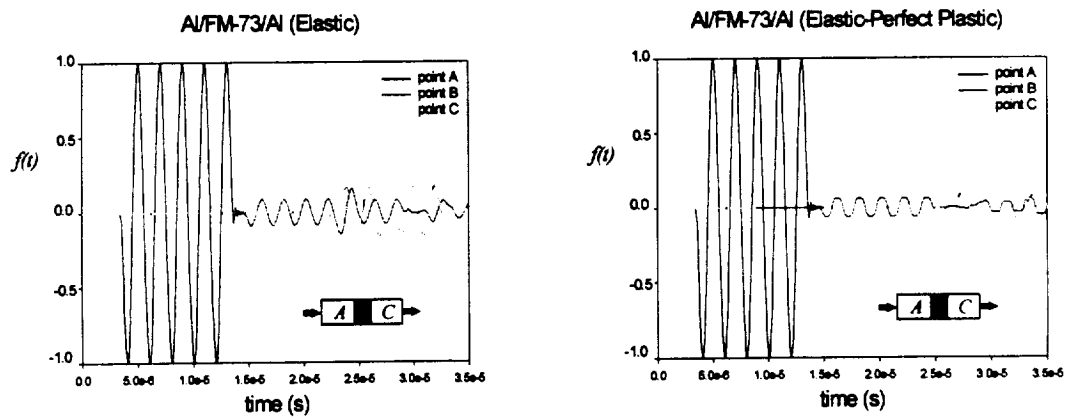


Fig.11 Responses at different points for 0.5MHz load

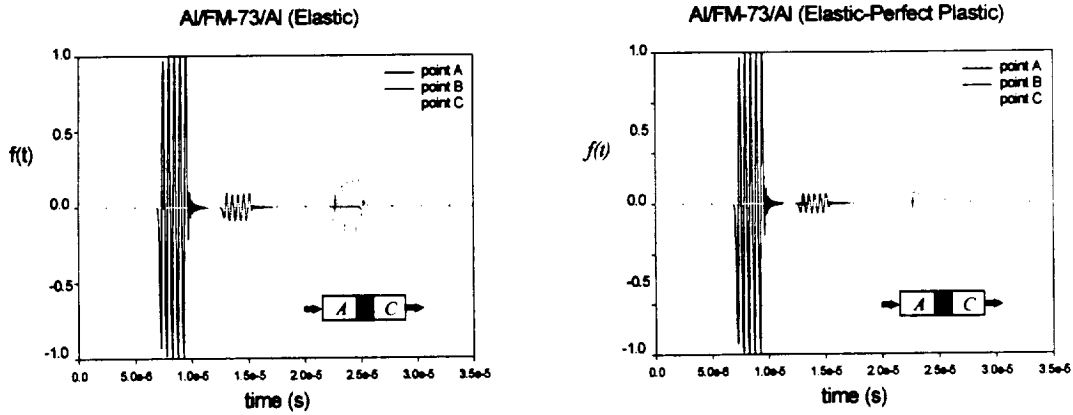


Fig.12 Responses at different points for 2.0MHz load

It is seen from Fig.11 and Fig.12 that the amplitude of the incident wave decreased significantly after passing through the adhesive layer. In the meantime, the yielding of the adhesive material indeed complicated the transmitted ultrasonic waves.

In order to see if there is any higher harmonic component caused by the material nonlinearly, the responses and their spectra at point C for the elastic and elastic-perfect plastic cases are compared in Fig.13 and Fig.14 for the two loading cases, respectively. The data are normalized by the magnitude of the fundamental component of their spectra.

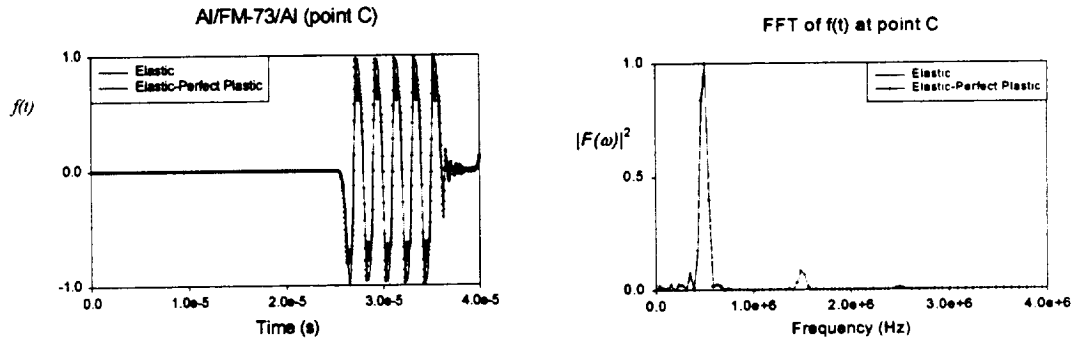


Fig. 13 Responses at point C and their FFT for 0.5MHz load

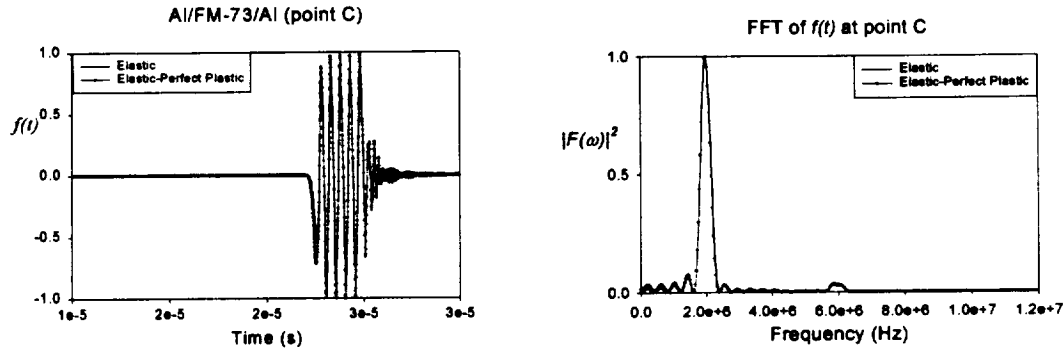


Fig. 14 Responses at point C and their FFT for 2.0MHz load

It is seen clearly from Fig. 13 and Fig. 14 that the higher order harmonics are generated by the non-linearity of the adhesive material, which is the plastic deformation of the adhesive material. Especially, significant 3rd and 5th order harmonics are generated. The magnitude of the 3rd order harmonics is about 1/25 of the fundamental one. However, the 2nd harmonic was not predicted by the FEM calculation. These numerical results seem to confirm what was observed experimentally, as described in the previous section.

Summary

The nonlinear responses of an adhesive joint was analyzed by the through transmission tests of ultrasonic wave and the finite element simulations. Two samples provided by NASA have been tested as received and after the accelerated temperature aging at 400°F for various periods of time. In these tests, a 40-cycles harmonic signal was generated by a 2MHz narrow-band PZT as the input. The output is received by a 2MHz broadband PZT. Due to material non-linearity in the adhesive caused by aging, higher order harmonics of the fundamental frequency is generated as the wave passes through the adhesive layer. The experimental results show that aging increases the magnitude of higher order harmonics of the fundamental frequency and the magnitude of the 3rd harmonic seems to correlates with aging time fairly well. To model the nonlinear effect of the adhesive layer, transmission through an adhesive joint was analyzed by the finite element method. Elastic-perfect plastic constitutional relation was used for the adhesive material. Results from the numerical simulation show that material nonlinearity does indeed generate higher order harmonics. In particular, the elastic-perfect plastic material behavior generates significant 3rd and 5th harmonics.

References

- J. D. Achenbach and O. K. Parikh, "Ultrasonic analysis of nonlinear response and strength of adhesive bonds," J. Adhesion Sci. Technol. Vol. 5, No. 8, pp. 601-618 (1991).
- L. Adler and P. B. Nagy, Review of Progress in QNDE, Vol. 10B, eds. D. O. Thompson and D. E. Chimenti (Plentium, New York, 1991), pp. 1837.

R. F. Anastasi and M. J. Roberts, "Acoustic Wave propagation in an adhesive bond model with degrading interfacial layers," MTL TR 92-63, U.S. ARMY Materials Technology Laboratory, 1992.

T. P. Berndt and R. E. Green, "Feasibility study of a nonlinear ultrasonic technique to evaluate adhesive bonds," Review of Progress in QNDE, 1997(in press).

A. Bostrom and G. Wickham, J. of NDE, Vol. 10, pp.139 (1991).

S. Hirose and M. Kitahara, Review of Progress in QNDE, Vol. 10B, eds. D. O. Thompson and D. E. Chimenti (Plenum, New York, 1992), p. 33.

G. M. Light and H. Kwun, "Nondestructive Evaluation of adhesive bond quality, State-of-the-art review," NTIAC-89-1, June 1989.

S. Pangraz and W. Arnold, "Quantitative determination of nonlinear binding forces by ultrasonic technique," Review of Progress in QNDE, Vol. 13B, eds. D. O. Thompson and D. E. Chimenti (Plenum, New York, 1994), pp. 1995-2001.

O. K. Parikh and J. D. Achenbach, " Analysis of nonlinearly viscoelastic behavior of adhesive bonds," J. of NDE, Vol. 11 (3/4), pp. 221-226 (1992).

Z. Tang, A. Cheng and J. D. Achenbach, "An ultrasonic technique to detect nonlinear behavior related to degradation of adhesive bonds," Review of Progress in QNDE, 1997(in press).